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Solar energy harvesting with the application of nanotechnology

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ABSTRACT

Nanotechnology is an enabling technology that provides an extensive range of resources to resolve the energy-related problems, as the developing components and appliances are smaller than 100 nm they provide the new ways to catch, store and exchange energy. Every day, the sun shines a huge amount of energy which is generated through a process of nuclear fusion. Even the sun radiates more energy in one second than people have practiced since the beginning of time. It has been noted that the technical potential of solar energy all over the world is many times larger than the current total primary energy demanded. In this study, the solar harvesting technology with the help of nano-materials has been thoroughly studied. The different types of modern solar collecting technologies that use the nano-materials effectively and successfully have been discussed. Among a number of devices, the solar collector, the fuel cell, photocatalysis and solar photovoltaic have used the nanomaterials to increase the efficiency. It is found that by using nanomaterials the incident radiation can be increased by 9 times while the efficiency of the solar collector is 10% higher compared to that of a conventional flat plate solar collector. The generation ways solar cell technologies have been also discussed here. At the end of this article, few challenges in using nanotechnology are also addressed in detail.

Contents

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1. Introduction

It has been nearly half a century since Nobel Prize winner Richard Feynman advocated widespread nano-scale research by delivering his famous speech "There's plenty of room at the bottom" in 1959, through which the nanotechnology concept first captured the world's attention [1]. Feynman described a process by which the ability to manipulate individual atoms and molecules might be developed, using one set of precise tools to build and operate another proportionally smaller set, and so on down to the needed scale.

The term "nanotechnology" was defined by Norio Taniguchi [2] as follows: "nanotechnology mainly consists of the process of separation, consolidation, and deformation of materials by one atom or one molecule". Since that time the definition of nanotechnology has generally been extended to include features as large as 100 nm. Dimensions between 1 and 100 nm are known as the nanoscale i.e., on the scale of 1 billionth to several tens of billionths of a meter as shown in Fig. 1. At the nanoscale, unusual physical, chemical, and biological properties can emerge in materials. These properties may differ in important ways from the properties of bulk materials and single atoms or molecules. Additionally, the idea that nanotechnology embraces structures exhibiting quantum mechanical aspects, such as quantum dots, has further evolved its definition. However, it specifically implies not only the miniaturization but also the precise manipulation of atoms and molecules to design and control the properties of the nanomaterials/nanosystems. These properties are completely different than those possessed by the bulk materials, producing custom-made devices with capabilities not found in bulk materials or in nature, or even to replicate some natural processes that have not been currently achieved through synthetic materials. Also in 1974, the process of atomic layer deposition, for depositing uniform thin films one atomic layer at a time, was developed and patented by Dr. Tuomo Suntola and co-workers in Finland. In the 1980s, the idea of nanotechnology as a deterministic, rather than stochastic, handling of individual atoms and molecules was conceptually explored in depth by Dr. K. Eric Drexler. His vision of nanotechnology is often called "Molecular Nanotechnology" (MNT) or "molecular manufacturing" [3].

Nanotechnology offers, for the first time, tools to develop new industries based on cost-effective and cost-efficient economies, thus seriously contributing to a sustainable economic growth. Focusing on the energy domain, nanotechnology has the potential to significantly reduce the impact of energy production, storage and use. Even if we are still far away from a truly sustainable energy system, the scientific community is looking at a further development of energy nanotechnologies. Energy experts predict that the world would need 30 TW of energy resources by the year 2050 to maintain economic growth [5]. Many scientists believe that the sun is the only candidate that can offer a fully developed solution for the energy crisis. Therefore, solar cells can be considered as a mainstream renewable energy resource once their manufacturing cost has decreased to an affordable level compared with other available energy resources. Parida et al. [6] reviewed different issues concerning solar cell technologies. At this stage, new initiatives on harvesting incident solar radiation with greater efficiency are needed to meet the global clean energy demand. Sequentially, solar cell technologies have evolved into three generations [7]. First generation solar cells are based on a single crystalline semiconductor wafer. Second generation solar cells utilize inorganic thin film structure in the cell assembly. They are cheaper to produce, but the efficiency, which is less than 14% in amorphous thin film solar cells, is lower than the efficiency exhibited by the single junction crystalline solar cell of the first generation that can reach as high as 27%. Theoretically, single junction cells should be able to exhibit a maximum efficiency of ~33% [8], a limit set by Shockley–Queisser thermodynamics. Thus, a new solar cell technology is required in order to achieve efficiencies greater than 33% with lower production cost. The onset of this breakthrough is the third generation solar cells [9]. Currently, the focus is on the third generation solar cells that can deliver economic, highly efficient cells that can emerge as a new technology in the near future as shown in Fig. 2 [10]. The relation between the solar cell production cost per square meter with the solar cell module efficiency and the cost per unit power is shown in Fig. 3 [11].

In this review, firstly we have focused on the applications of nanotechnology for different solar systems and storage systems. Secondly, we have emphasized how nanotechnology significantly contributes to enhance the performance of solar cell technologies. From the overall review, it is articulate that nanotechnology has played a significant role for reaping sustainable energy from solar radiation in different facets. Thus, this review aims to explore the role of nanotechnology in evolving solar energy by reconsidering its constraints.

2. Nanotechnology for harvesting solar energy

From the previous research, it has been shown that nanotechnology is a powerful tool for a host of the solar system in support of efficient, sustainable energy conversion, storage, and conservation, in terms of

- tailoring the interaction of light with materials and enabling the processing of low-cost semiconductors into devices such as photovoltaics.

Nomenclature

AR	antireflection
CNT	carbon nanotube
DASC	direct absorption solar collector
DSSC	dye-sensitized solar cell
DMFC	direct methanol fuel cells
D	dimension
EWT	emitter wrap-through
ESR	equivalent Series Resistance
FTO	fluorine-doped tin oxide
ITO	indium tin oxide
MQWSC	multiple quantum well solar cell
MST	metal to semiconductor transition
MFC	microbial fuel cell
MWNT	multi-wall carbon nanotube
NRAs	nanorod arrays
NCPSC	nanofluid-based concentrating parabolic solar collector
OPV	organic photovoltaic
PEMFCs	proton exchange membrane fuel cells
Pt	platinum
PCM	phase change material
PV	photovoltaic
QDs	quantum dots
QWs	quantum well
SWNT	single wall carbon nanotube
SSPCM	shape Stabilized PCM
SLSC	superlattice solar cell
SiNWs	silicon nanowires
TEM	thermoelectric modules
TEG	thermoelectric generator
TW	tera watt

- Making more efficient photocatalysts for converting sunlight into chemical fuels.
- Developing new materials and membranes for the separations needed in many energy applications.
- Converting chemical fuels into electrical energy (and vice versa), and improving energy and power density in batteries.
- Improving efficiency in areas from displays and solid state lighting to thermo-electric and friction.

At the application level of nanotechnology in solar systems, i.e. in active solar system, storage system and passive solar system, selected examples of the progress made in the previous years include those, discussed in the subsections below.

2.1. Active solar systems

Active solar systems are employed to convert solar energy into the other more useful forms of energy. This would normally be a transformation of heat or electrical energy. Inside a building this energy would be used for heating, cooling, or offsetting other energy usage or costs. Active solar systems use electrical or mechanical equipment for this transformation. The basic benefit of active systems is that controls (usually electrical) can be used to maximize their effectiveness. Solar collector, fuel cell, photocatalysis, solar photovoltaic and dye-sensitized solar cells are under the umbrella of active solar systems and are discussed in the following sections.

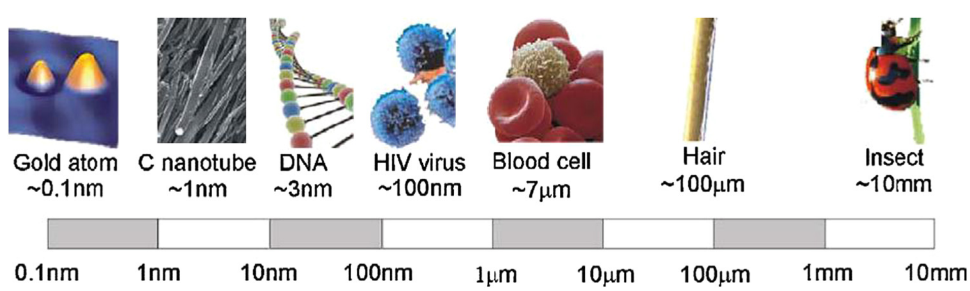


Fig. 1. The measured length of the real materials understanding the nano-particles' size [4].

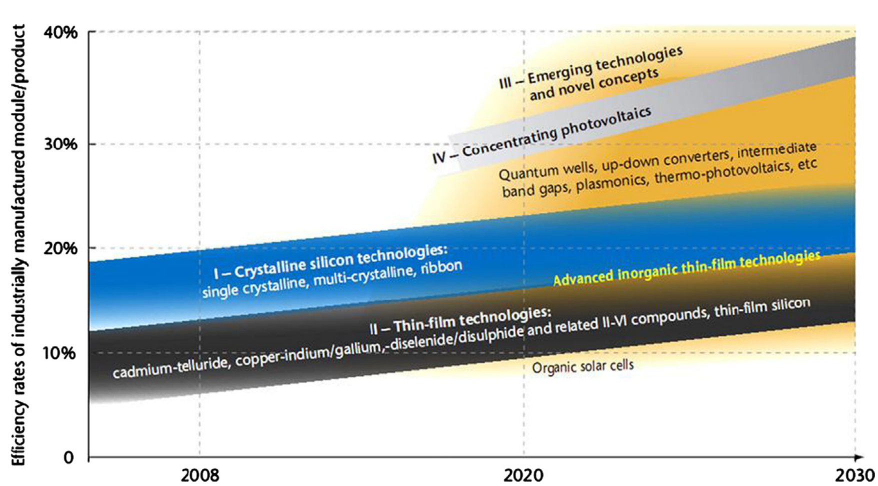


Fig. 2. Solar cell technology status and prospects [10].

2.1.1. Solar collector

Solar collectors are a particular sort of heat exchangers that absorb solar radiation by absorber – solid body, and cause the increase of its (absorber's) internal energy what gives the increase of temperature of the solid body (absorber) and in result the heat through heat conduction is transferred to the fluid. In recent times, numerous investigations were performed on flat-plate solar collectors, their attributes and their applications [12–14]. In order to advance their efficiency and output temperature, several methods have been proposed by the researchers.

Alongside the traditional methods improve the solar collector efficiency; one of the most successful methods is substituting the absorbing medium, water, with high thermal conductivity fluids (nanofluids). Nanofluid is defined as the fluid containing suspended solid nanoparticles [15]. Nowadays nanofluid is used in the solar collector and solar water heaters for efficiency, economic, and environmental aspects.

Khullar et al. [16] analyzed a linear parabolic solar collector with nanofluid as the heat transfer fluid. The collector modeled as a two dimensional steady system, and the finite difference method was employed to numerically solve the equations. They computed all the parameters quantitatively and compared the two cases (i.e., conventional parabolic collectors and nanofluid based collectors). Analysis revealed that nanofluid based collector performed better than the conventional collector under similar working conditions.

Taylor et al. [17] examined the performance of a nanofluid-based concentrating solar thermal system and compared with a conventional one. They stated that 10% improvement in efficiency might be possible by substituting the working medium, water, with nanofluid. They also resolved that for 10–100 MWe power plants, employing graphite/therminol VP-1 nanofluid with volume fractions of nearly 0.001% or less could be advantageous.

Tyagi et al. [18] studied a low-temperature nanofluid-based direct absorption solar collector (DASC) theoretically and described the influences of different parameters on its efficiency. They used a mixture of water and aluminum nanoparticles as the working fluid. In their analysis, they considered that the values of fluid inlet temperature, solar flux incident on the solar collector, and mass flow rate are 35 °C, 1000 W/m^2, and 1.2 kg/s, respectively. The investigation revealed that by adding nanoparticles to the working fluid, the efficiency rises surprisingly for low values of volume fraction of nanoparticles. For a volume fraction higher than 2%, the efficiency remains nearly constant, so adding more nanoparticles is not beneficial.

He et al. [19] studied the light-heat alteration features of water–carbon nanotube (CNT) and water–TiO_2 nanofluids. The experiment was performed under both sunny and cloudy weather conditions. The investigation outcomes showed excellent light heat conversion characteristic for nanoparticles weight concentration 0.5% of the CNT–H_2O nanofluid.

Otanicar et al. [20] conducted numerical and experimental analyses on a microscale direct absorption solar collector (DASC). They investigated the performance of a DASC for different nanofluids (carbon nanotubes, graphite, and silver) and then, compared the results with a conventional collector. Their experiment revealed that by adding small quantities of nanoparticles, approximately 0.5%, remarkable improvement of the efficiency could be possible.

Phelan et al. [21] analyzed and compared the theoretical and experimental results of a nanofluid-based concentrating parabolic solar collector (NCPSC) with conventional concentrating parabolic solar collectors under similar conditions. They injected 0.05 vol% aluminum nanoparticles suspended in Therminol VP-1 as the base fluid. They realized that 5–10% improvement in thermal efficiency of NCPSC could be conceivable when comparing it to a conventional parabolic solar collector.

Yousefi et al. [22] experimentally examined the consequences of Al_2O_3/water nanofluid on the efficiency of a flat-plate solar collector. They observed the effects of two different weight fractions of the nanofluid, including 0.2% and 0.4%, where the diameter of particles was 15 nm. Furthermore, they considered the effects on efficiency of Triton X-100 employed as a surfactant. Their results are as follows:

- 28.3% improvement in efficiency by using 0.2% weight fraction nanofluid as compared to water.
- For a wide range of the reduced temperature parameter, the efficiency of collector with 0.2% wt% nanofluid is higher compared to 0.4 wt%.
- Surfactant can enhance the efficiency by 15.63%.

Liu et al. [23] designed a novel evacuated tubular solar air collector to deliver air with high and moderate temperature. They integrated it with simplified compound parabolic concentrator and special open thermosyphon employing water based CuO nanofluid as the working fluid. Experimental outcomes revealed that the air outlet temperature and system collecting efficiency of

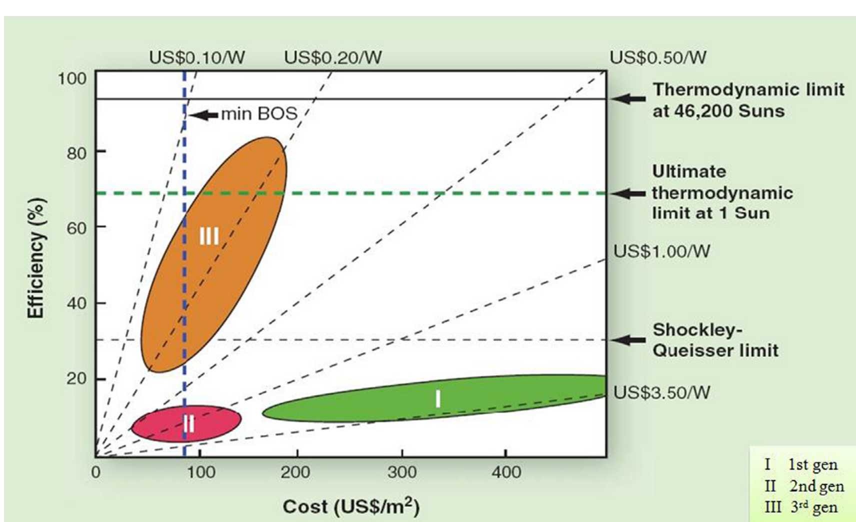


Fig. 3. The efficiency–cost trade-off for the three generations of solar cell technology [11].

the solar air collector using nanofluid as the open thermosyphon's working fluid were both higher than when using water.

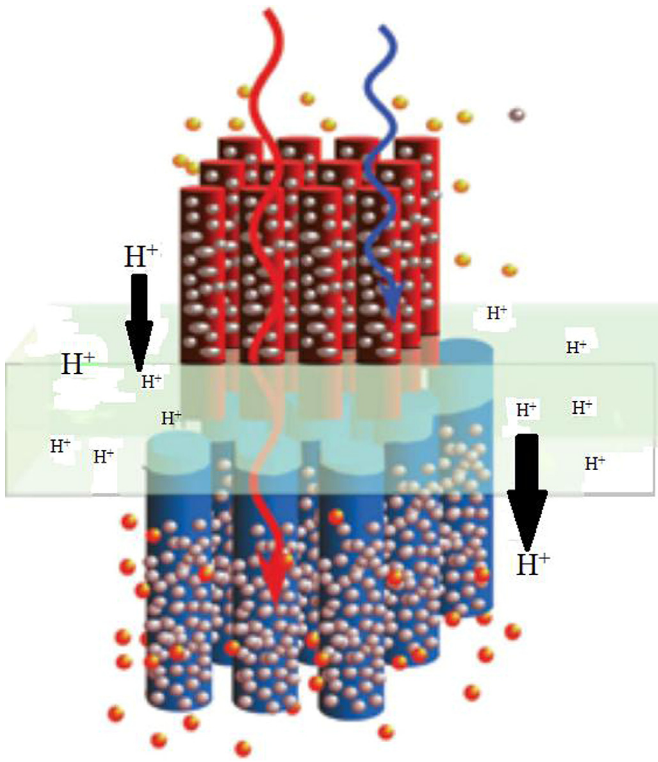


Fig. 4. A solar fuel cell [27].

2.1.2. Fuel cell

Fuel cells are energy altering appliances which have low emission and high efficiency. They have drawn attention of many researchers in recent decades because of gradual running out of fossil fuels, environmental conditions, and high-energy necessities all over the world. Membrane and electro-catalyst are the key materials for the success of fuel cell technology. Nanoparticle supported catalysts are assumed to be the most auspicious materials for catalysis in fuel cells. Speedy improvement of nanotechnology, particularly in the area of the synthesis of carbon nano-materials, will produce more stable and actively supported catalysts [24–26]. A typical solar fuel cell is shown in Fig. 4. A metal oxide anode (red) absorbs the blue section of sunlight, where it releases protons by oxidizing water. Silicon nanorod cathode (blue) absorbs the red section, which combines these protons with electrons to make hydrogen for fuel [27].

Supported catalysts exhibit superior stability and activity than the bulk metal catalysts. Carbon nanoparticle has good relative stability in both acidic and basic media, high specific surface area and good electric conductivity. Those properties are responsible for using carbon nanoparticle frequently as catalyst supports in fuel cells [28–31]. The stated reports have exposed that carbon nanotubes (CNTs) stayed higher for carbon blacks as catalyst supports for proton exchange membrane fuel cells (PEMFCs) [28,32]. For instance, 10% higher fuel cell voltage and twice the power density could be achieved by using a CNT supported Pt catalyst with 12 wt% Pt loading, than that of carbon black supported with 29 wt% Pt loading [33,29]. In contrast, several experiments have been performed on CNTs as supports for direct methanol fuel cells (DMFC) catalysts in recent years. Li et al. [34–36] stated that multi-wall carbon nanotube (MWNT) supported catalysts showed superior performance in DMFCs associated to those supported by carbon black (XC-72) under identical conditions both in

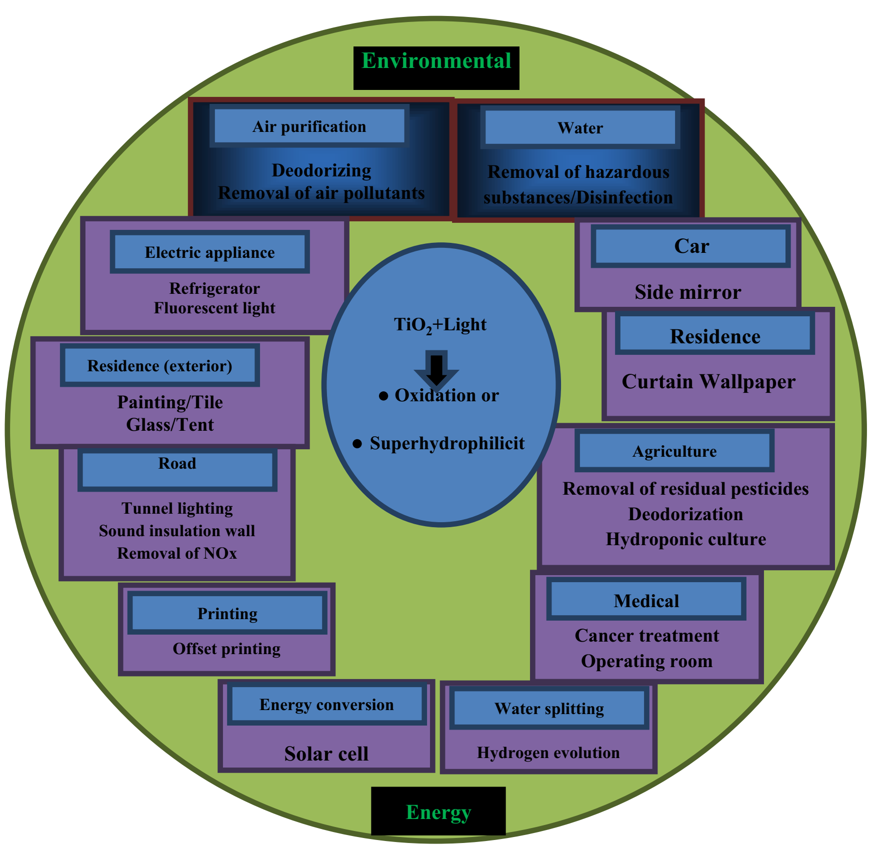


Fig. 5. Applications of TiO_2 photocatalysis [43].

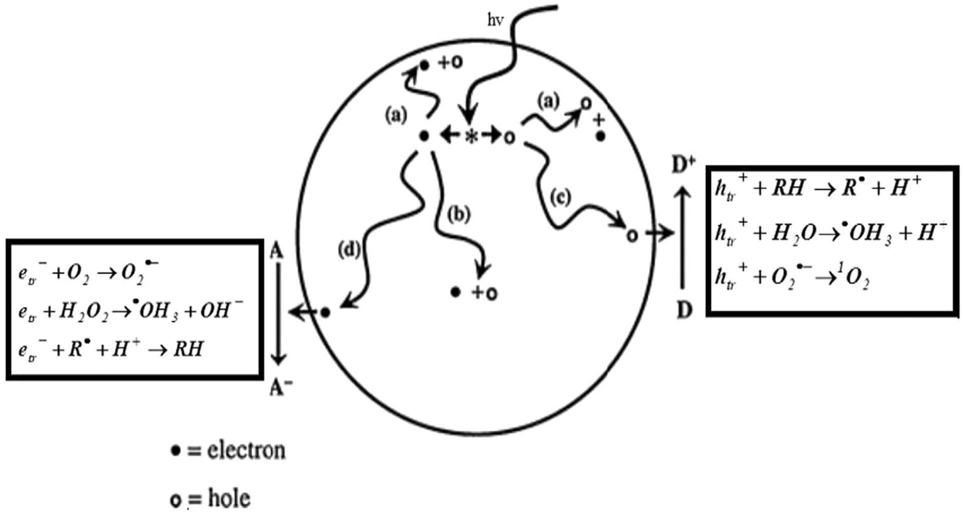


Fig. 6. Processes occurring on bare TiO_2 particles after UV excitation [43].

half-cell characterization and in a fuel cell performance test. Their outcomes displayed that the mass activity of Pt/MWNT catalyst at 0.7 V (versus DHE) in a single cell testing was 14.7 mA $mg_{(Pt)}^{-1}$, much better than Pt/XC-72 catalyst (2.2 mA $mg_{(Pt)}^{-1}$).

Zhao et al. [37] proposed a different methodology. They dispersed $MnO_2/SiO_2–SO_3H$ nanocomposite into the Nafion membrane to mitigate the degradation of membrane under fuel cell conditions. This nanocomposite improves fuel cell performance and membrane durability. The working principle of nanocomposite is to decompose hydrogen peroxide and quench the free radicals effectively, especially under low humidity conditions.

Fontananova et al. [38] categorized the inorganic heteropoly acid (HPA)-doped sulfonated derivative of a composite membrane prepared of an amorphous polyetherketone, SPEEK-WC. It could be upgraded with the interconnection of the ionic clusters in the polymeric matrix by delivering a special way for proton leaping, thus improving the proton conductivity and the ion-exchange capacity.

Kannan et al. [39] proposed a Nafion-based nanocomposite membrane. They introduced sulfonic acid-functionalized multiwalled (s-MWNT) carbon nanotubes into the polymer matrix. The proton conductivity was improved due to the combined effects of MWCNT and acid groups. Similar consequences were remarked with the introduction of CNTs prefunctionalized with Nafion into the Nafion matrix [40].

Sharma et al. [41] investigated a novel microbial fuel cell (MFC) considering that nanofluids as novel mediators were prepared by dispersing nanocrystalline platinum anchored carbon nanotubes (CNTs) in water. They compared the performance of the MFC using CNT based nanofluids and electrodes against plain graphite electrode based MFC. CNT based electrodes showed as high as 6-fold growth in the power density (2470 mW/m^2) compared to the graphite electrodes (386 mW/m^2).

2.1.3. Photocatalysis

The development of photocatalysis has been taking considerable attention of researchers for the last few years due to its low/less environmental pollution and higher amount of energy saving. A list of applications of TiO_2 photocatalysis is presented in Fig. 5.

Materials that have photocatalytic properties are currently being used to convert solar energy into chemical energy to further oxidize or minimize materials to get useful components together with hydrogen and hydrocarbons. Besides, they carry away

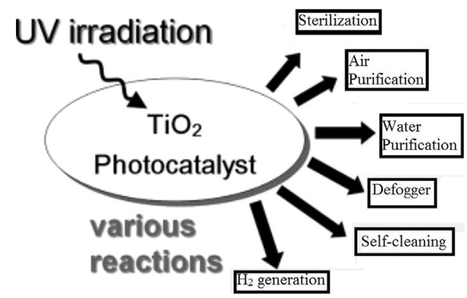


Fig. 7. Schematic illustration of applications of photocatalysis [46].

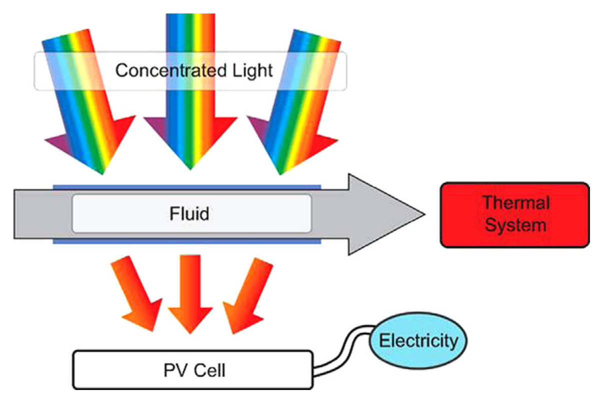


Fig. 8. Sketch of the de-coupled PV/T system (photovoltaic/thermal) [50].

pollutants and bacteria from the wall surfaces [42]. Nowadays TiO_2 nanoparticle is widely used in many applications due to its strong oxidizing abilities of decomposing organic pollutants such as superhydrophilicity, chemical stability, long durability, nontoxicity, low cost, and transparency to visible light. The photocatalytic properties of TiO_2 have originated from the formation of photogenerated charge carriers (hole and electron) which happens upon the absorption of ultraviolet (UV) light corresponding to the band gap. Fig. 6 shows the processes occurring on bare TiO_2 particles after UV excitation.

Nanostructured TiO_2 materials are widely used not only in photocatalysis, but also in dye-sensitized solar cells (DSSCs), lithium-ion batteries, and electrochromic displays [43–45]. TiO_2 nanosheets (two-dimensional structures), with a flat surface, high aspect ratio, low turbidity, and excellent adhesion to substrates, could

be effectively applied in self-cleaning glass. This unique structure might provide potential advantages for purification, separation and storage [43]. With the discovery of this phenomenon, the application range of TiO_2 coating has been largely widened. A schematic illustration of applications of photocatalysis is shown in Fig. 7.

2.1.4. Solar photovoltaic

Solar photovoltaic/thermal (PV/T) is one of the most prominent technologies to convert solar energy into heat and electricity at the same time. It is a hybrid structure that converts part of the sun's radiation to electricity and part to thermal energy [47,48]. Most of the solar radiation is either absorbed by solar cell or reflected back. Absorbed solar radiation raises its temperature which is responsible for the growing reverse saturation current, lowering open voltage, decreasing the energy gap, etc. [49]. Most of the current researches concentrate on cooling of solar cells and also recovering heat. The de-coupled PV/T system is shown in Fig. 8.

A review of the literature exposes that several researches have been carried out on the potential of nanofluids for cooling of different thermal systems such as electronic devices [51,52], automobile radiator [53], and microchannel heat sinks [54]. Therefore, using nanofluids to cool the PV/T system may be reasonable. Researchers are concentrating on nanofluid due to its improved or enhanced thermal conductivities. Table 1 lists some parameters of the PV/T system and PV module for comparison. PV module shows higher electrical efficiency but the overall efficiency of PV/T systems is extended several times than PV module due to heat generation besides electricity. The overall efficiency of the PV/T system is beyond 60% with a 2 mm thick liquid layer [49].

Xie et al. [55] studied the performance of a hybrid photovoltaic device comprising of P3HT/CdS/CdSe/TiO_2 nanorod array. They concluded that the CdS/CdSe quantum dots play an important role in improving charge separation and injection. It had been explained that coating CdS/CdSe quantum dots onto TiO_2 nanorods with P3HT to form p–n heterojunctions has largely increased the photovoltaic performance of the P3HT/CdSe/CdS/TiO_2 nanorod solar cells. The author also stated that the energy conversion efficiency was 0.57%.

2.1.5. Dye-sensitized solar cells

Dye-sensitized solar cell (DSSC) is a semiconductor photovoltaic device that directly converts solar radiation into electric current. The conversion efficiency of DSSC from visible light to electricity depends on the sensitization of wide bandgap semiconductors, photoelectrode, redox electrolyte and the counter electrode. DSSC mechanisms have extended under several improvements over the years in order to heighten the efficiency of the cell.

Table 1
Performance of PV/T systems and PV module [49].

Temperature efficiency	PV/T with a 2 mm thick liquid film	PV/T with a 4 mm thick liquid film	PV module
Cell temperature	27.3 °C	27.8 °C	23.1 °C
Temperature increase of liquid	7.5 °C	5.1 °C	
Electrical efficiency	14.7%	14.0%	15.9%
Thermal efficiency	47.2%	32.0%	
Overall efficiency	61.9%	46.0%	15.9%

Table 2
Photo-electrochemical parameters of the sensitized cells and TEM [57].

	Size (mm^3)	V_{OC} (V)	J_{SC} (mA)	FF(-)	η (%)	W (mW/cm^2)
DSSC	5*5*10	0.74	2.56	0.633	4.83	4.83
TEM	30*30*5	0.082	12.39	None	1.48	0.113

Chang et al. [56] introduced photo-electrochemical parameter as presented in Table 2– under simulated solar radiation on the basis of output data. It represents the conversion efficiency of DSSC and TEM of 4.83% and 1.48% respectively. Experimental results also showed, CuO coating onto TEG surface can enhance solar energy conversion efficiency and also heat conduction.

Recently, a novel TiO_2 mesoporous network with multilayer structure was proposed by Wang et al. [58]. In their work, multilayer films with different sized particles (diameter from ca. 100 nm to 23 nm) were fabricated and aligned layer by layer on the conducting glass to enhance light scattering. This structure effectively increased cell efficiency by 10.2%.

Usually, from arc discharge nanofluid synthesis system, TiO_2 nanofluid is synthesized. After that, nanofluid proceeds for receiving electrophoresis deposition to deposit TiO_2 nanoparticles on the indium tin oxide (ITO) conductive glass under normal temperature. A thin film of TiO_2 is formed [59]. In this process, nanoparticles diameter is approximately 20–50 nm and, nanofluid surface energy zeta potential is −22 mV to −29 mV [60].

Adachi et al. [61] presented a network structure of single-crystal-like TiO_2 nanowires designed via surfactant-assisted methods at a low temperature (353 K). The direction of crystal growth was controlled by changing the adsorption of surfactant molecules on the TiO_2 surface. Their experiment revealed that this plane exhibits excellent ruthenium dye adsorption, four times higher as compared to commercial product P-25, and overall cell efficiency of 9.3%.

2.2. Energy storage

Along with energy production, renewable energy systems such as solar or wind require the ability to store energy for reuse on many different scales. Electrical energy, which offers the greatest potential for meeting future energy demands as a clean and efficient energy source, can be stored with electrically pumping water into reservoirs, transforming it to potential energy and back. However, this is only possible for very large-scale localized storage. The use of electricity generated from renewable sources, such as water, wind, or sunlight, requires efficient distributed electrical energy storage on scales ranging from public utilities to miniaturized portable electronic devices. This can be accomplished with chemical storage (i.e., batteries) or capacitive storage (i.e. electrical capacitors). Nanostructuring can increase the efficiency of both storage, release of electrical energy, and the stability of electrode materials against swelling-induced damage from ion uptake.

2.2.1. Rechargeable batteries

Rechargeable batteries are energy storage devices used to power small electronic equipments such as cell phones and personal computers, where high power and light weight are important. These same attributes are required for electric vehicles, hybrid electric vehicles, power tool and backup power subsystems. Simplistically, a battery is an electrochemical device that generates DC through a coupled set of reduction–oxidation ('redox') reactions. The positive electrode is reduced ('captures electrons') and the negative electrode is oxidized ('releases electrons'). The battery consists of a positive electrode facing a negative electrode divided by a porous separator that prevents the electrodes from touching, and an ionic electrolyte, which is a conductive medium that ensures movement of the ions from one electrode to the other. Intercalation-based batteries using the small lithium (Li^+) ion are the most used. These batteries have at least one redox-active

electrode with an open crystal structure with 'holes' capable of intercalating Li^+. For example, oxidation of Co in $LiCoO_2$ expels Li^+ which is taken up in a graphite electrode. When the battery is charged, the Li^+ moves from the positive electrode to the negative one via the electrolyte. On discharge, the opposite occurs, releasing energy in the process. Ideally, the structure of the redox-active crystal should be capable of reversibly intercalating the small Li^+ ion.

Recently an exciting composite material that combines high energy capacity and flexibility was reported by scientists at Rensselaer Polytechnic Institute. The researchers found that they could combine nanotubes (which are highly conductive) with a layer of cellulose, the material used to make paper [62]. This way they were able to obtain 'paper batteries' which can be rolled or folded just like paper without any loss of efficiency. This opens the opportunity to have batteries molded to assume a particular form. Like all batteries, the paper version comprises electrodes, electrolyte, and a separator. The first electrode is formed by vertically aligned multiwalled carbon nanotubes, deposited on Si substrates. Plant cellulose is cast on top of the layer, solidified, and dried to form the porous separator. The middle paper layer is then impregnated with an ionic liquid which acts as the electrolyte and that can be an organic salt that is liquid at room temperature. The ionic liquid contains no water, so there is nothing in the batteries to freeze or evaporate. This increases the working temperature range of the battery, which can withstand extreme temperatures from 195 K to 450 K. To make a battery, the second electrode is formed by coating the paper side with lithium oxide. Interestingly the same material can be used to make a supercapacitor simply by folding the paper in half, so that there is a carbon electrode at both top and bottom.

The battery safety can be increased, if the graphite electrode in a lithium-battery is replaced with a nanostructured material inert toward the electrolyte. Nanotechnology can also be employed to use alternative active materials which are less expensive and non-toxic to the environment. For example, the non-toxic magnetite (Fe_3O_4) has been employed as an active material in a high-capacity Cu nano-architectured electrode [63].

2.2.2. Supercapacitors

Supercapacitors are an alternative way of storing electricity that can benefit from nanotechnology. They are needed in those devices that require rapid storage and release of energy, for instance hybrid-electric and fuel-cell powered vehicles. They are constructed by two electrodes immersed in an electrolyte, with an ion permeable separator between them. Each electrode–electrolyte interface represents a capacitor, so the complete cell can be considered as two capacitors in series. The focus in the development of these devices has been on achieving high surface-area with low matrix resistivity. The most remarkable property of a supercapacitor is its high power density, about 10 times that of secondary battery. The maximum power density of a supercapacitor is proportional to the reciprocal of its internal resistance. A number of sources contribute to the internal resistance and are collectively referred to as equivalent series resistance (ESR). Contributors to the ESR include the electronic resistance of the electrode material and the interface resistance between the electrode and the current-collector. Carbon, in its various forms, is currently the most extensively used electrode material in supercapacitors. A typical commercial supercapacitor can produce a power density of about 4 kW/kg[6]. Nanotubes can be used to increase the power density of supercapacitors, since the nanoscale tubular morphology of these materials can offer a unique combination of low electrical resistivity and high porosity in a readily accessible structure. Single-walled (SWNTs) and multi-walled (MWNTs) nanotubes are under investigation. Research has shown that the use of thin film electrodes with multi-walled aligned nanotubes increases the specific power density (laboratory results of 30 kW/Kg have been reported [64]), credit for the reduction of ESR.

2.3. Passive solar systems

In passive solar systems or building design, windows, walls, and floors are made to gather, store, and spread solar energy in the form of heat in the winter and decline solar heat in the summer. This is called passive solar system or climatic design because, compared with active solar heating systems, it does not involve the use of mechanical and electrical devices. The key to developing a passive solar building is to best take advantage of the local climate. Elements to be considered include window placement and replacement window type, warm insulating material, warm mass, and covering. Passive solar system techniques can be applied more easily to new structures, but existing structures can be tailored or “retrofitted”. In the below subsection, the function of nanotechnology in passive solar systems are briefly described here.

2.3.1. Phase change materials (PCMs)

PCMs deliver a large heat capacity over a limited temperature range and they could act like an almost isothermal reservoir of heat. As the temperature increases, PCMs change phase from solid to liquid. Since this reaction is endothermic, they absorb heat. When the temperature decreases, PCMs change phase from liquid to solid. This time they release heat, since this reaction is exothermic. The principle of PCMs use is very simple, but evaluating the effective contribution of the latent heat loads in the enhancement of the energy performance of the whole building is a challenge. PCMs are classified as organic, inorganic and eutectic. Organic PCMs are further described as paraffins and non-paraffins. The non-paraffins include a wide selection of organic materials such as fatty acids, esters, alcohols and glycols. Of most interest in this group is the fatty acids which are subdivided into 6 groups: Caprylic, Capric, lauric, Myristic, palmitic and stearic [65]. Inorganic PCMs are further described as hydrated salts and metallics (metals have too high melting temperatures for passive building applications). A eutectic is a minimum-melting composition of 2 or more components, each of which melts and freeze congruently forming a mixture of the component crystals during crystallization [66]. Eutectics PCMs are subdivided into organic–organic, organic–inorganic and inorganic–inorganic.

The effective use of PCM permeated wallboards in interior wall surfaces of building enclosure has gained impetus in maintaining the desired thermal environment in indoor environments. In this context, a comparative study between an ordinary room and phase change wall room was conducted by Shilei et al. [67]. Capric acid and lauric acid (fatty acid based) mixture in the proportion of 82:18% having freezing and melting temperatures of 19.138 and 20.394 °C was used as the PCM in this study. It has been observed that the room integrated with this PCM impregnated wallboards showed good performance in terms of maintaining the warmth and thermal comfort during winter. The heat loss effects from the room to the ambient in winter were minimized effectively. Also, the energy consumption rate of electrical heating utilities was reduced significantly. A new kind of PCM based tiles meant for stabilizing the indoor air temperature in winter was developed and patented by Ceron et al. [68]. This PCM tile would absorb the heat energy from sunlight in daytime and store them as a potential heat source for warming up the house during nighttime. Based on the analysis report it is seen that by varying the temperature of fusion the same PCM tiles can also serve as a heat sink in hot sunny days in summer. Collectively, this PCM tile could contribute

for overall energy conservation in buildings by means of passive cooling/heating. Zhu et al. [69] modeled a shape stabilized PCM (SSPCM) wall system and progressed with quantitative analysis of the energy performance and optimal control strategies for a real time building A/C system using this SSPCM envelope. Peak thermal load shaving and demand limiting control methodologies were examined based on the SSPCM thermal properties and characteristics. Two tropical climatic regions (Hong Kong and Beijing) with thermal load profiles were selected for analysis. Simulation of SSPCM enveloped buildings located in these regions shows improved thermal performance and indoor thermal comfort under time-based and energy-plus-demand-based pricing policies. Zhang et al. [70] evaluated the thermal response of a brick wall filled with PCMs under fluctuating outdoor temperatures using a thermal conduction model with phase-change based on the enthalpy-porosity technique. The results showed that, in comparison with a common solid brick wall, the thermal storage capacity of the PCM brick wall is higher, and the incorporation of PCMs in the bricks is beneficial for the thermal insulation, temperature hysteresis and thermal comfort for occupancy. Emerging economies in high need of housing and the thermal refurbishment of existing buildings in the developed countries are great opportunities for the development of new construction solutions with PCMs.

2.3.2. Glazing

Vanadium dioxide is a material that has exposed potential for use as an intelligent glazing material [71]. The material is organized by a metal to semiconductor transition (MST). In this arrangement, there is a structural change from a high-temperature rutile structure to a low-temperature monoclinic structure which effects in electrical conductivity and optical properties [72]. Semiconductor is used in the monoclinic phase and normally transparent to solar radiation, whereas metal is used for rutile and reflects solar radiation. Recently experiments have been performed to reduce the transition temperature of the vanadium dioxide MST by inserting dopants, of which tungsten has been the most successful dopant, reducing the MST by 20–25 °C per at% [73].

Saeli et al. [71] proposed gold nanoparticles to improve the properties of vanadium dioxide films. They used gold nanoparticles due to its surface plasmon resonance which was strongly absorbing and dependent on the dielectric properties. They concluded that by choosing the right shape and size nanoparticles, the properties of the resulting films could be tuned. Finally, they suggested that thermochromic films might be useful in warmer climates but were not suitable for cooler climates.

Presting and König [74] explained elaborately about the applications of nanotechnology in automotive glazing such as antireflection coating based on multiple nanolayers on glass, sun protecting glazing with infrared reflecting nanolayers embedded into sheets of glass. Besides, thermoplastic nanocomposite with nanoflakes (trade name Basell TPO-Nano) is used for stiff and light exterior parts.

2.3.3. Paint

For advance surface gratings, many commercial paint techniques are available. It can modify the thermal emission from a surface. These techniques have their specific capacities and confines and can be used for a variety of applications. Generally, "paint" is used for its liquid phase and once it is applied to a surface it is called a "coating". Mostly, paint is a dispersion of solid particles called "pigments" suspended in an organic medium called "resin." Most of the pigments are complex metal oxide and semiconductors. Many types of pigments, carbon, FeO_x, melanin, Zn powder, silicon, PbS organic soot (Degussa FW2) [75–80] are used in spectrally selective paints. TiO_2 (rutile titania) pigmented paints are the best for radiative cooling applications [81]. Impenetrability of these pigments is well discussed in [82]. Rutile titania pigments hosted in polymer matrix are used in many selective paints for radiative cooling and $FeMnO_x$ is the best paint pigment so far for solar thermal applications [83,84]. The high ingestion of these pigmentation in the solar energy spectrum makes them appropriate for heating applications.

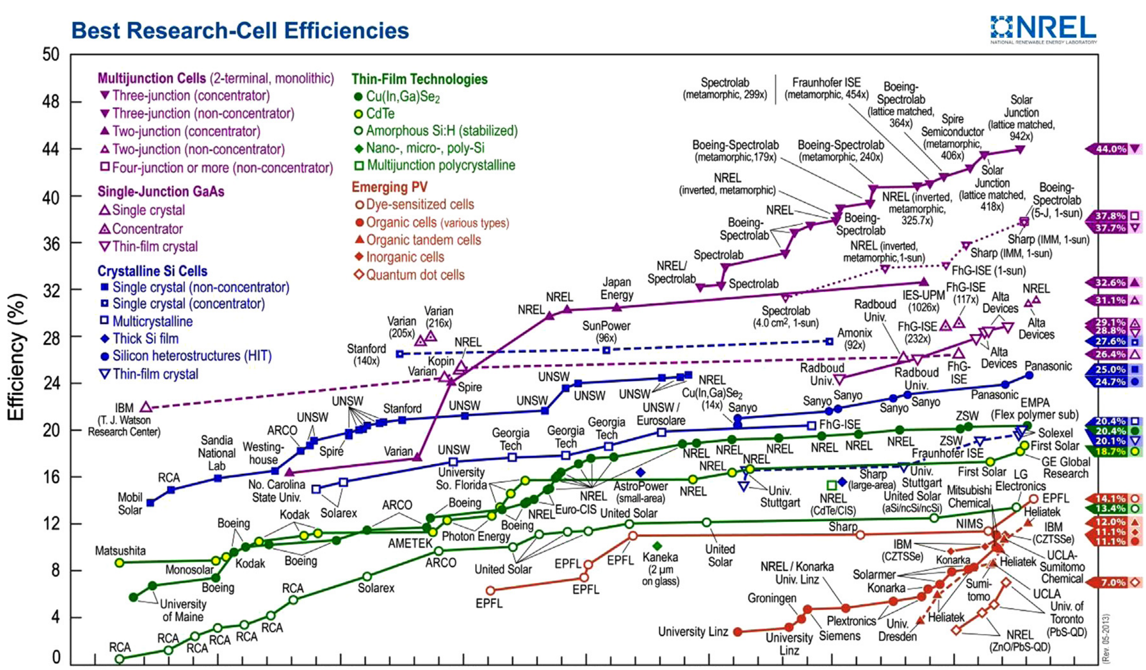


Fig. 9. Solar cell efficiencies for various technologies measured under standard conditions [85].

3. Solar cell technologies

Solar cells are usually divided into three main categories called generations. First-generation solar cell (fully commercial) use the wafer-based crystalline silicon (c-Si) technology, either single crystalline (sc-Si) or multi-crystalline (mc-Si). Second-generation solar cell (early market deployment) is based on thin-film solar cell technologies and generally includes three main families: (1) amorphous (a-Si) and micromorph silicon (a-Si/μc-Si); (2) Cadmium–Telluride (CdTe); and (3) Copper–Indium–Selenide (CIS) and Copper–Indium–Gallium–Diselenide (CIGS). Third generation solar cells include technologies, such as concentrating and organic solar cells that are still under demonstration or have not yet been widely marketed, as well as novel concepts are under development. Fig. 9 shows one indication of the success of the improvement of solar cell conversion efficiencies over time.

3.1. First generation solar cell technologies

The first generation of solar cell technologies is made of crystalline structure which uses silicon (Si) to produce the solar cells that are combined to make solar cells. However, this technology is not obsolete rather it is constantly being developed to improve its capability and efficiency. Monocrystalline, polycrystalline, GaAs and emitter wrap through (EWT) are cells under the umbrella of silicon crystalline structures and are discussed in the following sections.

3.1.1. Monocrystalline

This type of cell is the most commonly used, constitutes about 80% of the market and will continue to be the front-runner until a more efficient and cost effective solar cell technology is developed. It essentially uses crystalline Si p–n junctions. To manufacture monocrystalline silicon, a single crystal ingot is cultivated using the Czochralski method [86]. Due to the silicon material, currently attempts to enhance the efficiency are limited by the amount of energy produced by the photons since it decreases at higher wavelengths. Moreover, radiation with longer wavelengths leads to thermal dissipation and essentially causes the cell to heat up hence reducing its efficiency. The maximum efficiency of monocrystalline silicon solar cell has reached around 23% under standard test condition (STC), but the highest recorded was 24.7% (under STC). Due to the combination of solar cell resistance, solar radiation reflection and metal contacts available on the top side, self-losses are generated. After Si ingot is manufactured to a diameter ranging from 10 to 15 cm, it is then cut in wafers of 0.3 mm thick to form a solar cell of approximately 35 mA of current per cm^2 area with a voltage of 0.55 V at full illumination. For some other semi-conductor materials with different wavelengths, it can reach 30% (under STC). However module efficiencies always tend to be lower than the actual cell and Sunpower [87] recently announced a 21% full panel efficiency which is a record efficiency as determined by measurements done by the National Renewable Energy Laboratory (NREL).

3.1.2. Polycrystalline

Polycrystalline Si (pc-Si) wafers can be fabricated over large areas. Plasma processing of lower-cost pc-Si is used to form a highly transmissive surface and to increase the light absorption. Known as reactive-ion etching, this process allows about a 40% relative increase in absorption.

Polycrystalline cell is a suitable material to reduce the cost for developing solar cell; however, its efficiency is low compared to monocrystalline cells and other developing materials. Moreover, a polycrystalline cell has less flaws in metal contamination and crystal structure compared to monocrystalline cell [88]. Polycrystalline is produced by melting silicon and solidifying it to orient crystals in a fixed direction producing a rectangular ingot of polycrystalline silicon to be sliced into blocks and lastly into thin wafers. However, the final step can be abolished by cultivating ribbons of wafer thin size of polycrystalline silicon. Polycrystalline manufacturing technology was developed by Evergreen Solar [89].

3.1.3. Gallium Arsenide (GaAs)

The crystal structure of GaAs as a semiconductor compound is similar to that of Si. However, crystalline Si needs a thickness of 100 μm or more to absorb sunlight, whereas GaAs with a nearly ideal band gap of 1.43 eV only needs to be a few micrometers thick. With 25–30% energy conversion efficiency, GaAs exhibits a higher efficiency than crystalline Si. Since it is very resistant to heat and radiation damage, it is an ideal choice for concentrator systems and outer space applications. The expansiveness of single-crystal GaAs substrate is the main issue for the development of GaAs cells for terrestrial use. Two approaches to cost reduction include the fabrication of GaAs cells on low-cost substrates such as Si or germanium (Ge), and the growth of GaAs cells on the removable GaAs substrate. This removable GaAs substrate can be reused to produce other cells, and even make GaAs thin films similar to CIGS and CdTe thin films [90].

3.1.4. Emitter wrap-though cells

Emitter wrap-through cells have allowed an increase in efficiency through better cell design rather than material improvements in this technology, small laser drilled holes are used to connect the rear n-type contact with the opposite side emitter. The removal of front contacts allows the full surface area of the cell to absorb solar radiation because masking by the metal lines is no longer present. Several tests [91] showed that there are manufacturing gains by putting the contacts on the backs of the cell. Examples of companies using EWT technology are Advent Solar and Sunpower Corporation in the US. Using EWT has allowed a 15–20% increase in efficiency. One major disadvantage of such a technology is evident in large area EWT cells where this technology suffers from high series resistance which limits the fill factor.

3.2. Second generation solar cell technologies

Compared to the solar cells that are based on crystalline silicon, thin film technology is less expensive since it uses fewer materials and less manufacturing process. Since it uses less material, solar cell that is made for this technology is very thin—which is around 35–260 nm [92]. Five kinds of thin film cells have emerged as commercially important and are discussed in the following sections.

3.2.1. Amorphous silicon

Amorphous silicon (a-Si) is one of the earliest thin film technologies developed [93]. This technology diverges from crystalline silicon in the fact that silicon atoms are randomly located from each other [94]. This randomness in the atomic structure has a major effect on the electronic properties of the material causing a higher band-gap (1.7 eV) than crystalline silicon (1.1 eV). The larger band gap allows a-Si cells to absorb the visible part of the solar spectrum more strongly than the infrared portion of the spectrum. There are several variations in this technology where substrates can be glass or flexible SS, tandem junction, double and triple junctions, and each one has a different performance.

3.2.2. Amorphous-Si, double or triple junctions

It is considered that a-Si cells have lower efficiency than the mono- and poly-crystalline silicon cells. With the maximum efficiency achieved in the laboratory currently at approximately 12%, single junction a-Si module degrades after being exposed to sunlight and stabilizing at around 4–8%. This reduction is due to the Staebler–Wronski effect which causes the changes in the properties of hydrogenated amorphous Si [95]. To improve the efficiency and solve the degradation problems, approaches such as developing multiple-junction a-Si devices have been attempted [96]. This improvement is linked to the design structure of such cells where different wavelengths from solar irradiation (from short to long wavelength) are captured. The STC rated efficiencies of such technologies are around 6–7%.

3.2.3. Tandem amorphous-Si and multi-crystalline-Si

Another method to enhance the efficiency of solar cells and modules is the "stacked" or multi-crystalline (mc) junctions, also called micromorph thin film. In this approach two or more solar cell junctions are layered one on top of the other where the top layer is constructed of an ultra-thin layer of a-Si which converts the shorter wavelengths of the visible solar spectrum. However, at longer wavelengths, microcrystalline silicon is most effective in addition to some of the infrared range. This results in higher efficiencies than amorphous Si cells of about 8–9% depending on the cell structure and layer thicknesses. There has been a great push to move thin film Si solar panels in this direction and two deposition companies in particular provide the tools for such a process: Oerlikon and Applied Materials (AMAT) [97]. AMAT have developed tools that can produce thin film a-Si and micromorph panels of up to 5.5 m^2.

3.2.4. Cadmium telluride (CdTe) and cadmium sulfide (CdS)

CdTe as a polycrystalline semiconductor has a high light absorptivity level, i.e., only about 1 μm thick semiconductor can absorb 90% of the solar spectrum. Another advantage is its relatively easy and inexpensive manufacturing process. However, its conversion efficiency is low, similar to that of a-Si [13]. Small-area CdTe cells have efficiencies of greater than 15% [22] and CdTe modules have efficiencies of greater than 9% [23]. Some of the dominant problems of CdTe solar cell development include the difficulty of doping p-type CdTe, the difficulty in obtaining low-resistance contacts to p-type CdTe, the recombination losses associated with the junction interface [33], and cadmium toxicity-related precautions that have to be considered during the manufacturing process. The main problem in developing CdTe for solar application is the instability of cell and module performance. Recently, Tang et al. [35] fabricated cadmium sulfide core/copper sulfide shell nanowire solar cells using a low-temperature solution-based cation exchange reaction. The open-circuit voltage and fill factor, which determine the maximum energy that a solar cell can produce, promote the inexpensive and convenient manufacturing method of nanowire solar cells. These new nanowire solar cells also demonstrate 5.4% energy conversion efficiency, which is comparable to those of planar solar cells.

3.2.5. Copper indium diselenide (CIS) or copper indium gallium diselenide (CIGS)

Great improvements can be expected in the near future owing to the high flexibility of the design of compounds with defined properties in this material system (e.g., bandgap grading). A better understanding of the surface and junction properties of materials can lead to the development of various devices and result in new perspectives on ternary thin-film solar cells [98]. CIS is an effective material, but its complexity makes its manufacturing difficult. Safety can be considered as another concern in the manufacturing process. Due to the composition, density, and adhesion properties of CIS, it is useful in solar cells [99]. CIGS (indium incorporated with gallium – increased band gap) is multi-layered thin-film composite. Unlike basic p–n junction silicon cell, these cells are explained by a multifaceted hetero-junction model. The best efficiency of a thin-film solar cell is 20% with CIGS [100] and about 13% for large area modules [101]. The biggest challenge for CIGS modules has been the limited ability to scale up the process for high throughput, high yield and low cost. Meyer and van Dyk [102] also conducted an experiment to investigate the performance of CIS and other thin film material. The result from the experiment conducted is that CIS only degrades by 10% compared to other thin film material after an outdoor exposure of 130 kWh/m^2. The absorption coefficient of $CuInSe_2$ is greater than 10^5 cm^{-1}.

3.3. Third-generation solar cell technologies

Third-generation solar cell technologies are at the pre-commercial stage and vary from technologies under the demonstration (e.g. multi-junction concentrating solar cell) to novel concepts still in need of basic Research and Development (R&D) (e.g. quantum-structured solar cells). There are a number of novel solar cell technologies under development that rely on using quantum dots/wires, quantum wells, or superlattice technologies [103,104]. These technologies are likely to be used in concentrating solar cell technologies where they could achieve very high efficiencies by overcoming the thermodynamic limitations (Shockley–Queisser limit of 31–41% power efficiency) of conventional (crystalline) cells. However, these high efficiency approaches are in the fundamental materials research phase and selected solar cell technologies are also briefly reviewed here.

3.3.1. Quantum dots

Quantum dots (QDs) are attractive for solar cell applications due to their ability to enhance light absorption via multiple energy levels and extend the absorption edge into the infrared range [105,106]. Theoretical modeling of QDs solar cell has predicted an increase in the efficiency up to ~64% for a well-adjusted intermediate band. Quantum dots are minute crystal composites which have numerous particular semiconductor properties that are a few nanometers in size. These nanoparticles are generally created out of substances such as titanium oxide (TiO_2) and zinc oxide (ZnO_2), and also vary in dimension from 1 to 20 nm [107,108]. To carry the electrons out there are different methods in which QDs are incorporated and can be used in solar cells [109]. They have a promising prospective regarding exchanging the solar energy efficiency in a more economical way. In the direction of drastically improved solar technology, QDs have intense potential, and energy is a more genuine alternative energy source. The novelty of quantum dots is integrated in solar cells to make them highly resourceful energy turbines [110].

U.S.A NREL developed a new device with the concept of multiple electron generation or carrier multiplication (MEG) using lead selenide (PbSe) QDs in 2011 and it was also able to fabricate very efficient solar cells. This solar cell invention has recognized significant attention for its quantum efficiency which is greater than 100%. It is much privileged than usual silicon solar cells and from the investigation it is observed that most obtainable quantum dot solar cell performance was nearer to 10% [111]. It was possible to develop higher efficiency solar cell by the combination of carrier multiplication techniques and this introduced unique quantum qualities of QDs.

At present, the quantum dots are used to design the "energy transfer" solar cell. QDs have the ability to absorb different

wavelengths of light from sunlight because quantum dots have different volume and size. In solar cells, quantum dots are put in different layers with varying size. Due to the varying dimensions of QDs, they absorb different wavelengths of sunlight. As a result, more light is produced in the cell. Because of the stable state at p–n junction, electron–holes cannot hop and hence the efficiency of the cell is increased [112].

Using QDs it is possible to create next generation solar cell made with a low cost and efficient alternative. Because of different dimensions of quantum dots, they possess the ability to adjust their band gap and absorb varying wavelengths. The band gap energy depends on the size of quantum dots and it is observed that this is inversely proportional [111]. Hence, it captures a broader solar spectrum and harvests more solar energy in the cell. The author found that QDs have a great prospective in enhancing the efficiency (with 44%) of solar cell [113].

3.3.2. Quantum wells

A quantum well (QWs) is a potential well with only discrete energy values. QWs are formed in semiconductors by materials such as gallium arsenide (GaAs) sandwiched between two layers of a material with a wider band gap, like aluminum arsenide (AlAs) [114]. QWs within the solar cells manage charge carriers electrons and holes (e–h) that usually swing in three dimensions to two dimensions. The assortment of electrons and holes minimal is identified by the width of the semiconductor employed, generally which varies from 1 to 10 nm.

Courel et al. [115] extend a new approach where GaAs/GaInNAs multiple-quantum wells and superlattice are added inside the inherent part of conventional GaAs p–i–n solar cells. First, a GaAs/GaInNAs multiple quantum well solar cell (MQWSC) was described in order to research the conversion efficiency as a function of wells width and depth. A discussion about N fraction and quantum well width to reach the maximum of the solar cell performance is addressed. Second, a theoretical study of the GaAs/GaInNAs superlattice solar cell (SLSC) viability was considered where the effective density of states and the absorption coefficient for the SL structure are calculated in order to determinate the J–V (current density–voltage) characteristic. The SLSC conversion efficiency is compared with the maximum conversion efficiency obtained for the MQWSC. Finally, they present GaAs/GaInNAs SLSC conversion efficiency as a function of solar concentration, showing an amazing increment in its performance [116].

To enhance the light collection competence of InGaN-based MQWSCs Lin et al. [117] applied ZnO nanorod arrays (NRAs) as the antireflection (AR) layer. The conversion efficiency increased ~36% by 1.1-μm-long NRAs because of its advanced optical transmission. The effectiveness gets better of InGaN-based MQWSCs utilizing quantized inexpensive ZnO NRAs which confirmed a hopeful nanofabrication for AR glazes for exploiting light collection competence [117].

3.3.3. 'Smart' coatings

In the last few years, nanostructured components and nanoparticles have revealed up as the necessary substances for electro-optical programs and improvement of system performance, in particular by using the light control factors of the nanomaterials. The program locations that are being personalized significantly consist of amazing defending gadgets (e.g., electrochromic, photochromic, and thermochromic devices), display engineering, and acknowledging. Despite the huge amounts of work in previous times on amazing defending gadgets, and in particular on electrochromic gadgets and thermochromic fenestrations, for visual indication or idea control, programs stay restricted because of gradual reaction time and nonuniformity in the case of huge locations. Electrochromic and electrophoretic or suspended-particle windows seem highly promising for dynamic daylight and solar energy applications in buildings based on the achieved transmittance modulation ranges. The transmittances in the solar spectrum, the guaranteed number of cycles and the maximum window sizes are similar to the commercial products of both technologies. The maximum transmittance as well as the modulation range in the visible spectrum is much higher for electrochromic windows, though. On the other hand, the transmittance modulation has been found poor in commercial liquid crystal windows. In addition, the liquid crystal windows have been found instable for UV radiation and as a result inappropriate for long-term exterior building applications. Liquid crystal and suspended-particle windows share the same disadvantages: Both need an electric field to be maintained as long as the transparent mode of the glass is required, resulting in a higher energy consumption compared with electrochromic windows which normally only require an electric field during switching.

Currently, based on this literature survey, electrochromic windows seem to be the most promising state-of-the-art technology for daylight and solar energy purposes. The reliability of the current commercially available windows has been proven, their properties are within expectations and room for improvements has been demonstrated in the literature. The windows have been found to be able to reduce up to 26% of lighting energy compared with well-tuned daylighting control by blinds, and around 20% of the peak cooling loads in hot climates as California (USA). However, little is known about their efficiency in colder, e.g. Nordic, climates.

Gasochromic windows have recently been developed and show promising results. Due to its simple device structure and the absence of transparent conductors, very high transmittance modulation ranges compared with the short research period have been achieved. This may also mean that future commercial gasochromic windows may become an economically attractive high performance alternative for current smart window technologies. However, negative aspects such as the use of gas and a limited available number of cycles must be mentioned.

Concurrently, nanostructured cells would gradually become a "game changing" engineering to make cells that are cost-effective and impressive, offering a considerable substitute vehicle for our ever enhancing energy needs [118,119]. Nanotechnology used to inactivate power managing can be found in the form of 'smart' components such as electrochromic and photochromic coverings used for darkening screens. They reduce inside heating during summer, so less air-conditioning is required to keep cool, thereby leading to major power saving [120,121]. Another example of nanotechnology used as intelligent coverings is the use of a family of wavelength-selective films that are used for the production 'heat mirrors'. One of these components is indium-tin-oxide (ITO), an infrared absorber. A 0.3 μm ITO covering on glass provides more than 80% indication for the wavelengths prevalent in the sunshine. The qualities of the screen can be diversified by changing the width and material structure of the covering, so that a mixture of components could be used to produce intelligent windows that can be used both in summer and winter [121,122].

3.3.4. Carbon nanotubes and fullerenes

The past two decades have served as a test-bed for measuring the physico-chemical properties of carbon in reduced dimensions starting with the beginning of fullerenes (0D), followed in chronological order by carbon nanotubes (1D), carbon nanohorns, and,

most recently, by graphene (2D) and poised for wide-ranging applications [123,124]

Fullerenes were the first of the molecular sp^2 carbon allotropes to be isolated and identified, opening a new era in material science. However fullerenes have mostly sparked interest as n-type semiconductor materials in organic field effect transistors [125,126] and organic photovoltaic cells [127,128]. In the context of the fullerenes, organic photovoltaics (OPV) have gained extraordinary attention due to their immense potential in low-cost solar energy conversion devices. For typical bulk heterojunction solar cells involving films of conjugated polymers and fullerenes or electron donor–acceptor conjugates spin-coating has emerged as the top choice to process them on the electrode surfaces.

Conceptually, 1D carbon nanotubes (CNT) are considered as small strips of graphene sheets that have been rolled up to form perfect seamless single walled nanocylinders. Vertically aligned CNTs can be used in hybrid solar cells to increase surface area while maintaining good contact with the electrode. In this respect, they are very close to the idealized geometry for solar cells [129]. The use of CNTs in dye sensitized solar cells (DSSCs) is well documented [130–133]. Zhang et al. [134] prepared DSSC devices using counter electrodes made from double-walled CNT using a printing process. Polymer OPV devices have also been made using transparent electrodes made from CNTs.

The youngest representative of synthetic carbon allotropes is 2D graphene. Single graphene layers were first prepared successfully in 2004 by simple mechanical exfoliation of graphite using Scotch Tape [135]. An ideal single layer of graphene has an optical transmittance of 97.7% [136]. ITO and FTO are the most common transparent conducting films, which are used as front electrodes in inorganic, organic and dye-sensitized solar cells. However, the need for substitutes is increasing due to the limited availability of raw materials (indium) and high production cost. Graphene has been considered as a promising material for producing transparent conducting films, having high flexibility [137], remarkably high electrical mobility and optical transparency, and carbon being an inexpensive source material. The transparency of graphene films varied from 97% (single graphene layer) to 84% (seven graphene layers). Using ultrathin and high-mobility graphene films, graphene/CdS and graphene/ZnO composite films were fabricated and used in glass/graphene/ZnO/CdS/CdTe/(graphite paste) solar cells. For this configuration, a photovoltaic power conversion efficiency of 4.17% was obtained, demonstrating that the graphene-based ultrathin films can be used as a new low cost front electrode material for photovoltaic devices [138]. Although graphene has the potential to replace ITO in OPV devices, one of the main drawbacks of graphene films is their poor hydrophilicity, leading to a negative effect on the construction of solution-processed devices. Recently, large area, continuous, transparent and highly conducting few-layered graphene film produced by chemical vapor deposition was used as an anode in organic photovoltaic devices to overcome this drawback by chemically treating the graphene layer [139]. Dye-sensitized solar cells have been extensively studied as a low-cost alternative to commercial, silicon-based solar cells. Interesting results were recently obtained using graphene monolayers as active constituents of dye-sensitized solar cells [140,141]. Large, solution-processable graphene quantum dots as light absorbers for photovoltaic devices were introduced by Yan et al. [142]. These solution-processable, black graphene quantum dots were synthesized using solution chemistry and used as sensitizers for solar cells.

Carbon, in the form of fullerene, has already given us one of the most efficient electron acceptors for bulk heterojunction OPV devices with more than 8% conversion efficiency [143]. As summarized herein, it may yet provide the material for replacing rare metal-based electrodes and interface layers.

3.3.5. Nanowires

Nanowires have recently attracted considerable attention for solar energy harvest, conversion and storage due to their unique physical and chemical properties compared to their bulk counterparts. Size and morphology dependent properties, such as quantum confinement effects in semiconductor nanostructures, provide a rational approach toward a highly efficient solar energy conversion process [144,145]. Nanowires have attracted considerable interest because they represent the smallest dimension for efficient charge generation, separation and transportation. One dimensional nanostructure possesses the unique chemical, structural and physical properties that make them ideally suited for solar energy harvest and conversion [146,147]. The unique geometry of nanowire arrays can allow for low optical reflection and enhance the light trapping and absorption within nanowires arrays [146–148]. These unique characteristics motivated nanowires as potential materials for solar energy conversion.

For solar energy conversion silicon nanowires (SiNWs) have significant potential due to its features [144,149,150], even though SiNWs performance is lower than bulk Si or micrometer-scale wires. These one-dimensional materials provide an ideal platform to study PV characteristics of various semiconductor junctions at the nanoscale. These studies can offer exciting potential in efficient utilization of solar energy. The material selection, optimized geometry and architecture, as well as surface treatment, are important factors to be addressed to realize the full potential of the one-dimensional homogeneous and heterogeneous nanowires for highly efficient solar energy conversion.

4. Challenges of utilizing nanotechnology

Wide range of application of nanofluid appears promising, but researchers face various challenges for the development of this field such as [50,151]

- the deficiency of similarity among experimental results from several groups.
- Poor long term stability of nanoparticle suspension.
- Poor theoretical knowledge on key energy transport mechanisms.
- Increased pressure drop and viscosity, lower specific heat and higher cost of nanofluids.
- Green technology for high volume production of nanofluids.
- Convective heat transfer of nanofluid with experimental studies is needed.
- Besides this, some parameters should be carefully considered while conducting experimental studies, i.e. change in thermophysical property with respect to temperature, particle migration and Brownian motion of particles.

However, the most challenging aspects of nanotechnologies are the characteristics of the nano-materials, such as [24]

- stability for long time of nanoparticles dispersion
- Raised pressure drop
- Raised pumping power
- Thermal performance of nanofluid in turbulent and fully developed region
- High viscosity
- Low specific heat
- Thermal conductivity
- Nanofluid economy
- The problem arises in manufacturing of nanofluids.

Nanoparticles production is considered as another challenge in the progress of nanotechnologies. It may limit the advantage of

high surface area by agglomeration of larger particles. To overcome this limitation, additives can be used. Base fluid with nanoparticles is often mixed with additives for further application. Mixing of additives also has some disadvantage. It can change particle's surface properties and may contain an impermissible level of impurities. To specify the exact properties, larger samples are needed to test [152].

Furthermore, ultrasonic vibration is commonly used to enhance dispersion and breaking the clusters of nanoparticles. It is obvious that the duration and the intensity of the ultrasonication will affect the dispersion characteristics; however, the clusters will form again and their size will increase in time after ultrasonication [153]. Therefore, by using apparently the same samples, different results could be obtained just by varying the time between the ultrasonication and measurement of nanofluid characteristics. A strong temperature dependence of thermal conductivity of nanofluids is very important and has potential to expand the possible application areas of nanofluids. Additional important issues during application of nanofluids are flow erosion and settling. Before the commercialization of nanofluids, possible problems associated with these issues should be investigated and resolved [154].

5. Conclusions

To perceive heat transfer characteristics and specify new and the identical application of nanofluids further theoretical and comprehensive studies are needed. In this paper, a review on utilization of nanofluids and their effectiveness for harvesting solar energy has been studied. The main findings of this study are as follows:

- The resource of solar energy is eternal; however the technology for harnessing this enormous energy is not so much developed.
- By using nano-fluids, the efficiency of the direct absorption solar collector can be increased up to 10%.
- The first generation of solar cell technologies is fully commercialized and the second generation is an early market deployment; however the third generation is still under demonstration stage.
- A proper technology should be developed to match with the characteristics of the nano-fluids so it will be possible to harness the maximum amount of energy from the Sun.
- Many challenges are to be resolved and unforeseen opportunities are to be pursued in the future. Further research still has to be done in the synthesis and applications of nanofluids so that they may be applied as predicted.
- Nevertheless, there have been many discoveries and improvements identified about the characteristics of nanofluids in the surveyed applications. However, in the future, convective studies must be performed with metallic nanoparticles with different geometries and concentrations to consider heat transfer enhancement in laminar, transition and turbulent regions.

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